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(54) POLARIZATION INDEPENDENT LIGHT MODULATION MEANS USING BIREFRINGENT CRYSTALS

(71) We, WESTINGHOUSE ELECTRIC CORPORATION of Westinghouse Building, Gateway Center, Pittsburgh, Pennsylvania, United States of America, a company organised and existing under the laws of the Commonwealth of Pennsylvania, United States of America, do hereby decalre the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to improvements in a light modulation system for randomly polarized light.

In applicant's United Kingdom patent 1,066,612 there is described and claimed a light modulation system for electronically controlling the passage of polarized light. It is also disclosed there as applied to the resonant optical cavity of a stimulated emission of radiation device, as well as to a simple system for modulating the light intensity of a polarized light beam.

That system has gone into very wide usage because of its capability of very high frequency operation and its capability of operating at what is considered in the art as relatively low modulation voltages. In both that system and in the present one the light modulation is effected by direct polarization modulation. In the system which is disclosed in the above-mentioned United Kingdom patent the type and/or degree of polarization of the incident light must be known in order that proper adjustments of components can be made to accomplish the desired modulation.

In addition to applicant's previous patent there is a United States patent 3,325,646 which is perhaps the best representation of the prior art attempting to attain the objectives of the present invention. That patent describes a multiply reflected path electro-optical light modulator. Also that patent and other similar ones, such as United States patent 3,259,015 describe systems which are capable only of modulating a selected linearly polarized component of incident light. This is a serious disadvantage in these prior devices since they cannot produce complete cut-off of randomly polarized light.

An object of the present invention is to provide a light modulation system in which a complete cut-off of randomly polarized light is obtained.

Another object is to provide an improvement in the general type of light modulation means disclosed in the prior art which eliminates the energy loss due to the necessity of using a polarizer and/or analyzer in the light path.

With these objects in view, the invention resides in a light modulation system for an incident light beam having its electric vector at any orientation, said system comprising two uniaxial birefringent electro-optical crystals having substantially identical mutually orthogonal first, second and third optic axes, the third axes being the unique optic axes and being arranged mutually at 90° and disposed perpendicular to the path of said incident light beam, the first and second axes being semi-axes of the refractive index ellipsoid induced on application of an electric field, the first axis of one crystal being collinear with the second axis of the other crystal, the collinear axes of the two crystals being parallel to said path of said light beam; means for applying simultaneously an electric field along the third axis of each of said crystals; and first means for receiving said incident light beam and resolving said beam into orthogonally plane polarized component beams in spaced parallel paths passing through said collinear crystals.

The invention will become more readily apparent from the following description of a preferred embodiment thereof shown by way

of example in the accompanying drawings, in which:

Fig. 1A and Fig. 1B are schematic illustrations of the essential components of the invention when used as a light modulating device or a light valve in a non-reflecting path; Fig. 1A illustrating the light paths when the modulator is un-energized, and Fig. 1B representing the energized situation;

Fig. 2 is a schematic illustration showing the same corresponding components and supplementing Figures 1A and 1B;

Fig. 3 is a sectional elevation view of Fig. 1B looking in the direction of arrows at the plane III—III;

Fig. 4 is a sectional elevation view of Fig. 1B looking in the direction of the arrows at the plane IV—IV;

Fig. 5 is a sectional elevational view of Figure 1B looking in the direction of the arrows and at the plane V—V;

Fig. 6 is a diagrammatic illustration of an embodiment of the invention applied as a Q-switch for a Fabry-Perot cavity of a stimulated emission of radiation amplifier or oscillator; and

Fig. 7 is a diagram showing the paths of incident and reflected light rays in the embodiment of the invention shown in Fig. 6.

Briefly, the present invention provides an improved electro-optical light modulating means which may be used as a light valve and is particularly adapted for use in modulating the Q of a Fabry-Perot cavity of a stimulated emission of radiation amplifier, or oscillator. The system is capable of effecting continuous variation in the transmission of light or of effecting pulse modulations thereof. The system is capable of operating at very high speeds in the manner of an "on-off" switch to abruptly cut off, or on, light energy reflected back and forth in the resonant optical cavity of a stimulated emission radiation amplifier or oscillator.

An illustrative embodiment of the present invention utilizes the electro-optical light modulation system described in applicant's aforesaid patent in combination with a double refracting birefringent crystal for resolving the incident beam and in which the crystal geometry is preferably so selected that maximum displacement is obtained between the ordinary and the extraordinary rays to the end that the sensitivity, reliability and resolution of a system will not be sacrificed. The objective of the present invention is to provide such an electro-optical system which is capable of switching and/or modulating all of the light energy in a randomly polarized light beam and which is capable of operating at very high speed in the microwave frequency range.

Referring to Figures 1A and 1B, there is shown an embodiment of the invention wherein the system is to be used where it is desired to switch or modulate an incident light beam represented at 1 being propagated from left to right. The system includes double refracting birefringent crystals 2 and 3 between which is interposed a polarization modulator 4. The polarization modulator 4 is the same as that described and claimed in applicant's patent referred to above.

Since polarization modulators operate on polarized light beams only it is common to think, and was heretofore thought generally, that the type of polarization modulators represented by the reference numeral 4 were not satisfactory to modulate randomly polarized light not to serve as a light valve for all of the light energy in a beam of randomly polarized light.

In the present invention the modulator 4 is at least one crystal able to control or modulate all of the energy of a beam of unpolarized or randomly polarized light.

This comes about by reason of the fact that randomly polarized or unpolarized light may be resolved into two linearly polarized vectors vibrating in planes orthogonal to each other so that at any point in space an time, the randomly polarized light can be considered as the integrated vector sum of two orthogonally polarized light beams. The above vector analysis, although known before, has not heretofore been considered to make it possible to modulate all of the light energy in a randomly polarized light beam. The present invention takes advantage of the fact that although all birefringent crystals are double refractive, certain of them are more double refractive than others.

The present invention contemplates the utilization of such birefringent crystals for the elements 2 and 3 in which the orthogonal components of light incident upon them are spatially separated sufficiently so as to carry out the objectives of the present invention. In order to accomplish this it is necessary to choose the proper crystal material in which the crystal geometry is optimized by carefully orienting the incident light beam 1 with respect to the optic axis of the crystals so as to provide the maximum separation. For the purpose of this invention it has been found that a biaxial crystal which gives an angle separation of approximately 9.5° for a light beam having a wavelength from 4,000 to 15,000 angstroms can provide sufficient separation within the practical limits of the crystal to carry out the objectives of this invention. The separation of the orthogonal components of a light beam are illustrated in the several figures of the drawings.

From the description so far it will be seen that for the particular orientation of crystals 2 and 3, which are also of appropriate dimensions and index of refraction

the manner in which the O and E rays are refracted in the crystal 3 when the rays were proceeding from left to right as previously discussed in connection with Figure 1.

From the previous discussion of Figure 1, it follows logically that the O and E rays will be doubly refracted in the opposite sense in which they were doubly refracted in Figure 1 when the rays were proceeding from left to right. Accordingly, referring to Figure 6 it will be seen that the reflected E ray proceeding from the polarization modulator 18 toward the left hand side will be refracted so that it emerges from the left hand side of crystal 17 at the optical axis and combines with the O ray and the combined rays will proceed to the left through the laser rod 12 and will be reflected back from the mirror 8. This will be repeated while the polarization modulator 18 is unenergized. In this state, optical feedback is allowed and laser action will occur.

Now assume that polarization modulator 18 is energized. As the light beam 22 proceeds from the laser rod 12 toward the right and passes through the crystal 17, the O and E rays will be generated again as in Figure 3. The energization of the modulator 18 causes the O and E rays to revert to an O′ and E′ ray as shown in Figure 7. As the rays O and E continue to the left through the crystal 17 they will retain their same polarization that they had when they left the polarization modulator 18 and the crystal 17 will refract each of the two rays, which are indicated as O′ and E′ in Figures 4 and 7. It will be apparent from these other two figures that the E′ ray is now in the same position as the original incident O ray and the O′ ray is in the same position as the original E ray. During propagation through crystal 17, the O′ and E′ rays will be further displaced from one another and symmetrically displaced from the axis of the laser rod 12 in Figure 6 as the rays emerge from the left hand side of crystal 17. In this state optical feedback is prevented from passing through the laser rod 12 and laser action will not occur.

For a more complete description of the manner in which the polarization modulator 18 operates on the spaced linearly polarized O and E rays, reference is now made to Figure 2.

The polarization modulator 18 comprises a pair of suitable electro-optical crystals which are uniaxial and become biaxial when subjected to an electric field. The preferred type of crystal is the dihydrogen phosphase type such as KDP or ADP. For those readers who are not entirely familiar with the type of crystal it might be said that the uniaxial crystals normally have one optic axis along which no relative phase retardation takes place when the light passes parallel to the axis in the absence of an applied electric field. The electro-optic effect in crystals of this type is the result of induced birefringence which occurs when the electric field in applied to the crystal along a particular axis. Birefringency is a consequence of anisotropy in the crystal indices of refraction along the principal crystal axis. Electro-optic crystals are best described in terms of the Fresnel index ellipsoid which has axes proportioned to the principal indices of refraction in the crystal. Plane polarized light incident upon a birefringent crystal will experience double refraction and phase retardation between the orthogonal components of the incident light vibrating along the principal optical axis in the crystal. In uniaxial crystals, two of the indices of refraction in the ellipsoid are equal. Therefore, no birefringence occurs for light propagating perpendicular to the plane of the equal indices. This propagation direction determines the optic axis of the crystal. Crystals in which the principal indices are unequal are biaxial, that is they have two optic axes. An electric field applied parallel to the Z-axis of a uniaxial electro-optic crystal causes the indices of refraction for light vibrating parallel to the respective X and Y axis to be altered so that the X and Y indices are no longer equal.

It will be noted from Figure 2 that the X axis of crystal 20 is axially aligned with the Y axis of crystal 21. The two crystal system has the properties of the optical axis of inducing a phase difference between the orthogonal component beams of a linearly polarized beam propagating along an optical path and which is linearly polarized for optimum modulation in conventional electro-optic shutters employing the Pockels effect. By the proper dimensioning of the crystals and by applying the appropriate electric field, dependent upon the crystal dimensions, it is possible to produce π radians phase difference between the emerging components of linearly polarized input light. Under this condition, the resultant output polarization is rotated 90° with respect to the input polarization. For use of the invention simply as a light modulator or a light shutter, an appropriate analyzer well known in the art would be placed in the path of the light beams emerging from the crystals 20 and 21 to effect light modulation. On the other hand, when the light modulator is used in association with the optical cavity of a laser as in Figure 6, the electro-optical modulator is able to control the amount of light which is regeneratively coupled back into the laser medium. However, it must be noted that the light beam undergoes two phase retardations in the modulator 18 due to the round trip passage and consequently the phase retardation for each passage needs only be 90°.

Preferably, although not necessarily, the crystals 20 and 21 are elongate and have a

for the spectrum of light energy under consideration, the ordinary ray O and the extraordinary ray E will follow paths as illustrated in Figures 1A and Fig. 1B for the unenergized and energized states respectively, of polarization modulator 4.

Assuming that there is no energization applied to the polarization modulator 4, the electric vectors of the extraordinary E ray and the ordinary O ray will be as shown respectively in Fig. 3. Both of the rays E and O will pass straight through the modulator 4 with the same relative position between their vectors. As the E ray enters the crystal 3 it will be deviated back to the optical axis OA as indicated in Fig. 1A, (collinear with incident ray 1) and the vector components will be combined into a single emergent beam 6 with random polarization.

Now assume that the polarization modulator 4 is energized, that is, it is in what may be termed the closed position as far as light valve action is concerned. The light paths for the O and E rays for the energized condition of the polarization modulator 4 are illustrated in Figure 1B. As in the previous instance, the incident beam 1 will be split into the two spaced rays O and E and their light paths will be laterally spaced as indicated in Figure 3. For a particular value of modulating voltage applied to the polarization modulator 4, the O ray will become an E′ ray and the E ray will become an O′ ray as illustrated in Figure 4. Note here that the primed letters denotes components of the incident ray that are effectively rotated by 90°. As the rays O′ and E′ propagate through birefringent crystal 3 further displacement of the light paths will occur as indicated in Figures 1B and 5 and both rays will emerge from crystal symmetrically displaced from the axis OA. Clearly then, with the O′ ray and E′ ray each displaced from the axis OA, by a distance X and no light is within an aperture of radius X from the axis OA.

Under these conditions with the ordinary and extraordinary rays displaced from the optical axis one obtains light valve action along the optical axis OA.

The situation for operation of the light valve just described will now be described in connection with Figures 6 and 7 where the present invention is applied to the Fabry-Perot cavity of a stimulated emission radiation amplifier.

When the present invention is used with a polarization modulator 4 in the Fabry-Perot cavity a convenient modulation system is provided. The modulator is one capable of very high speed operation, such as is described and claimed in applicant's aforesaid patent. Although the polarization modulator 4 may be exactly the same as that in the patent, the operation is slightly different here only to the extent that the spaced orthogonal components of two light rays are effectively rotated simultaneously whereas in the patent only one light beam is involved.

Referring to Figure 6, a stimulated emission of radiation system using the present invention includes two mirrors 8 and 9, forming a Fabry-Perot resonant optical cavity one of which mirrors is totally reflecting and the other one, for example, mirror 8 may be partially reflecting to provide means for coupling light out of the cavity in the form of a beam indicated at 11 of enhanced coherency. The system also includes a body of negative temperature medium, such as the laser rod 12, which may be optically pumped by the output from a suitable flash tube 13 energized by a suitable power supply 14 in the manner well understood in the art. The polarization modulator 18 is the same as the modulator 4 of Fig. 1 and is associated with a birefringent crystal 17 having the same characteristics as the crystal 2, previously mentioned in connection with Figure 1. The modulation of the output light beam 11 is controlled by the output from a suitable electronic driver 19 in the manner well understood in the art, and particularly set forth in the aforesaid applicant's patent.

The modulator 18, is illustrated in more detail in Figure 2 and is formed of a pair of electro-optical uniaxial crystals 20 and 21. In the illustration of Figure 2 the incident light beam 22 may correspond to the beam 1 in Figure 1. Further relating Figure 2 to Figures 1 and 6, a double refracting crystal 24 corresponds to the crystal 2 of Figure 1 and crystal 17 of Figure 6. The electro-optical crystals 20 and 21 in Figure 2 corresponds to the device 18 in Figure 6. When the unpolarized light beam 22 is incident upon the crystal 24 the double refraction will take place and two light paths, one the ordinary ray O and the other the extraordinary ray E, will be generated as previously described in connection with Figure 1. For purposes of illustration, let us assume that the electric vectors of the O and E rays are as indicated in Figure 3. Also there should be a remark here that the incident light beam 22 may represent the light beam proceeding to the right emitted from the laser rod 12 shown in Fig. 6.

As the light beam 22 proceeds through the crystal 17 in Figure 6 (which corresponds to the crystal 24 in Figure 2) the two rays O and E will be generated and if the polarization modulator 18 is not energized, that is zero potential across the terminal 33 and ground 28 of Figure 2, the two components would then be reflected from the mirror 9 and would be returned to the right hand side of the crystal 17. Then as the reflected light beams proceed to the left in Figure 7, the O and E rays will be refracted in a manner similar to but exactly opposite to

square cross section. They may have a rectangular cross section as long as the dimensions along the Z-axes, parallel to which the potential is applied, are the same.

In the illustrated embodiment in Figure 2, the potential may be applied across the terminals 20a and 20b of the crystal 20 and the terminals 21a and 21b of the crystal 21. Terminals 20b and 21b are common to input lead 33 and a suitable potential is applied between this lead 33 and ground 28 to which the terminals 20a and 21a of the two respective crystals are connected.

If a comparison is made between this application and aforesaid applicant's patent, it will be noted that in the patent the system is used with a light beam which is linearly polarized, the plane of polarization being represented by a vector at 45° with respect to the Y and Z axis of the first crystal and X and Z axis of the second crystal.

The significant difference between the present invention and the above-mentioned patent is that the incident light beam, indicated at 1 in Figure 1 and at 2 in Figure 6 in the present invention need not be polarized. This is a very great advance forward in the art because in the construction which is disclosed in the above-mentioned patent, with any course of unpolarized light it is necessary to throw 50% thereof. In the present instance, by adding the birefringent crystals 2 and 3 of Figure 1, or only the crystal 17 of Figure 6, any incoming light can be modulated electrically. Should the incoming incident beam be linearly polarized as one example of any polarization and be strictly parallel to one of the axes as in Figure 1 and 6, a single ray will be transmitted through the system and modulation can be effected as in the system of the above-mentioned patent. On the other hand, when the incident light beam is randomly polarized the crystal 2 in Figure 1 and the crystal 17 in Figure 6 resolves the incoming beam into two separate rays with the electric vector of two rays being orthogonal to each other as indicated in Figure 3. We now have two linearly polarized components of light each of which is acted upon separately by the polarization modulator 4 or 18.

The theory of operation of applying the potential across the crystals 20, 21 is to be found in British Patent Specification 1066612.

In an embodiment of the present invention reduced to practice, the crystals 20 and 21 were 1″×1/4″×1/4″ in size and optically finished to laser rod tolerances. The calculated voltage necessary to achieve a 90° rotation of a ruby laser beam (λ=6943 A.) is 1200 volts and this agreed very well with the experimenting value. Under normal Q switching conditions, the crystals were biased at approximately 1100 volts, maintaining the optical shutter in the closed condition. An activating pulse lowered the bias voltage to approximately 300 volts which was sufficient, for all practical purposes, to open the optical shutter and permit laser action.

WHAT WE CLAIM IS:—

1. A light modulation system for an incident light beam having its electric vector at any orientation, said system comprising two uniaxial birefringent electro-optical crystals having substantially identical mutually orthogonal first, second and third optic axes, the third axes being the unique optic axes and being arranged mutually at 90° and disposed perpendicular to the path of said incident light beam, the first and second axes being semi-axes of the refractive index ellipsoid induced on application of an electric field, the first axis of one crystal being collinear with the second axis of the other crystal, the collinear axes of the two crystals being parallel to said path of said light beam; means for applying simultaneously an electric field along the third axis of each of said crystals, and first means for receiving said incident light beam and resolving said beam into orthogonally plane polarized component beams in spaced parallel paths passing through said collinear crystals.

2. A light modulating system as claimed in claim 1 including means for reflecting said orthogonally plane polarized component beams back through said crystals to said first means where they are recombined only if their polarization has not been modulated.

3. A light modulating system as claimed in claim 1 including second means for receiving said component beams after they have passed through said collinear crystals.

4. A light modulation system as claimed in any of claims 1—3 wherein said first means includes a birefringent element.

5. A light modulation system as claimed in claims 3 or 4 as dependent on Claim 3 wherein said second means includes a birefringent element for receiving light from said parallel paths and recombining them into a single light beam collinear with said incident light beam when the crystals are not subjected to an electric field.

6. A light modulation system as claimed in any of claims 1 to 5 including means for modulating the polarization of the component beams by modulating the means for applying an electric field.

7. A light modulation system as claimed in any one of the preceding claims wherein said crystals are disposed so that the electric vector of each orthogonal component is at 45° with respect to said first and second axes of said crystals mutually at 90° disposed perpendicular to the path of said light paths.

8. A light modulation system as claimed in any one of the preceding claims includ-

ing means for providing said incident light beam from stimulated emission of radiation.

9. A light modulation system for an incident light beam having its electric vector at any orientation substantially as hereinbefore described with reference to Figures 1A, 1B and 2, and Figures 6 and 7 of the accompanying drawings.

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2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

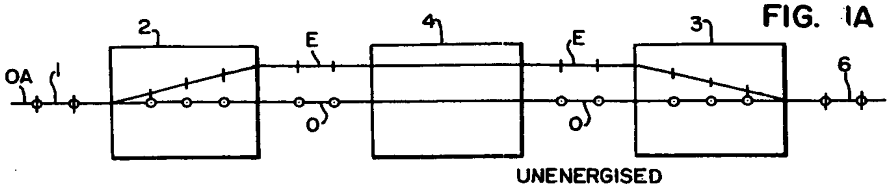

FIG. 1A

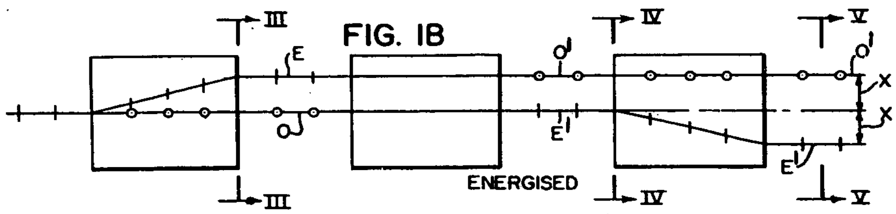

FIG. 1B

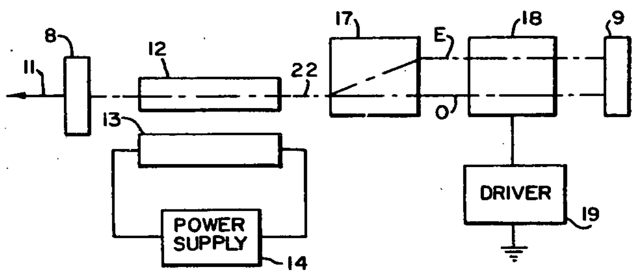

FIG. 6

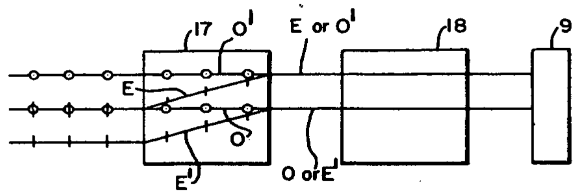

FIG. 7

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2 SHEETS *This drawing is a reproduction of the Original on a reduced scale.*

Sheet 2

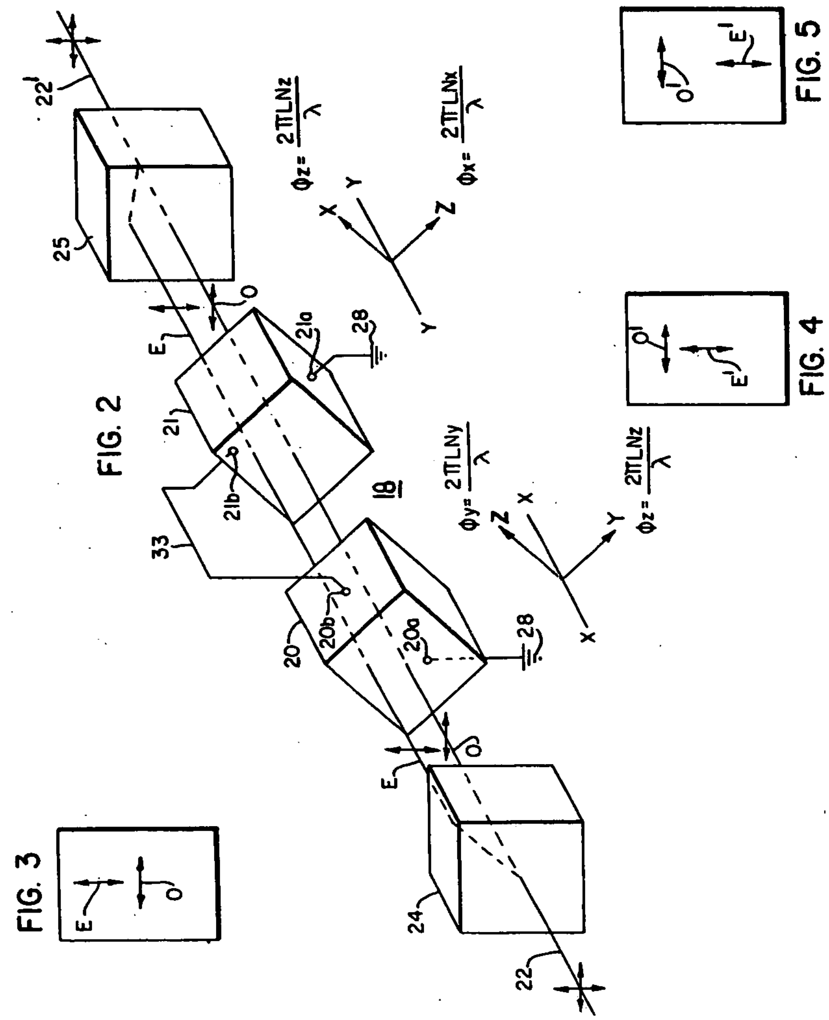

FIG. 2

FIG. 3

FIG. 4

FIG. 5